

# Neutrino flux predictions for known Galactic microquasars

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## ABSTRACT

It has been proposed recently that Galactic microquasars may be prodigious emitters of TeV neutrinos that can be detected by upcoming km<sup>2</sup> neutrino telescopes. In this paper we consider a sample of identified microquasars and microquasar candidates, for which available data enables rough determination of the jet parameters. By employing the parameters inferred from radio observations of various jet ejection events, we determine the neutrino fluxes that should have been produced during these events by photopion production in the jet. Despite the large uncertainties in our analysis, we demonstrate that in several of the sources considered, the neutrino flux at Earth, produced in events similar to those observed, would exceed the detection threshold of a km<sup>2</sup> neutrino detector. The class of microquasars may contain also sources with bulk Lorentz factors larger than those characteristic of the sample considered here, directed along our line of sight. Such sources, which may be very difficult to resolve at radio wavelengths and hence may be difficult to identify as microquasar candidates, may emit neutrinos with fluxes significantly larger than typically obtained in the present analysis. These sources may eventually be identified through their neutrino and gamma-ray emission.

*Subject headings:* X-ray: binaries—acceleration of particles—neutrinos

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## 1. Introduction

Microquasars are Galactic X-ray binary (XRB) systems, which exhibit relativistic radio jets (Mirabel & Rodríguez 1999; Fender 2001a). These systems are believed to consist of a compact object, a neutron star or a black hole, and a giant star companion. Mass transfer from the giant star to the compact object through the formation of an accretion disc and the presence of the jets make them similar to small quasars, hence their name “microquasars.” The analogy may not be only morphological; although there is no obvious scaling, it is common thinking that the physical processes that govern the formation of the accretion disc and the ejection of plasma into the jets are the same for both systems. Local, Galactic microquasars may therefore be considered as nearby “laboratories,” where models of the distant, powerful quasars can be tested. Microquasars are associated with several classes of XRBs, and differ in their time behaviour. Some, like SS433, are persistent sources, while others appear to be intermittent (GRS 1915+105) or periodic (LS I +61°303). In all cases, however, the observed radiation from microquasar jets, typically in the radio and in some cases also in the IR band, is consistent with non-thermal synchrotron radiation emitted by a population of relativistic, shock-accelerated electrons.

The composition of microquasar jets is still an open issue. The synchrotron emission both in the radio and in the IR is consistent with near equipartition between electrons and magnetic field, which is also implied by minimum energy considerations (Levinson & Blandford 1996). However, the dominant energy carrier in the jet is presently unknown (with the exception of the jet in SS433). Scenarios whereby energy extraction is associated with spin down of a Kerr black hole favor  $e^\pm$  composition (although baryon entrainment is an issue). However, the pair annihilation rate inferred from the estimated jet power implies electromagnetic domination on scales smaller than roughly  $10^9$  cm in the superluminal sources, and requires a transition from electromagnetic to particle dominated flow above the annihilation radius by some unspecified mechanism (Levinson & Blandford 1996). Alternatively, in scenarios in which an initial rise of the X-ray flux leads to ejection of the inner part of the accretion disc, as widely claimed to be suggested by the anti-correlation between the X-ray and radio flares seen during major ejection events, e-p jets are expected to be produced. A possible diagnostic of e-p jets is the presence of Doppler-shifted spectral lines such as the  $H_\alpha$  line observed in SS433, proving the presence of protons in the jets of this source. Unfortunately, detection of such “smoking gun” lines from jets having Lorentz factors well in excess of unity (as is the case in the superluminal microquasars) may be far more difficult than in SS433, as the lines are anticipated to be very broad ( $\Delta\lambda/\lambda \gtrsim 0.1$ ). Furthermore, the conditions required to produce detectable flux in such sources may be far more extreme than in SS433. Another diagnostic of hadronic jets, namely the emission of TeV neutrinos, has recently been proposed by Levinson & Waxman (2001). They have shown that, for

typical microquasar jet parameters, protons may be accelerated in the jet to  $\sim 10^{16}$  eV, and that the interaction of these protons with synchrotron photons emitted by the shock accelerated electrons is expected to lead to 1–100 TeV neutrino emission. The predicted fluxes are detectable by large,  $\text{km}^2$ -scale effective area, high-energy neutrino telescopes, such as the operating south pole detector AMANDA (Andres *et al.* 2000) and its planned  $1 \text{ km}^2$  extension IceCube ( see IceCube Proposal), or the Mediterranean sea detectors under construction (ANTARES, see ANTARES Proposal; NESTOR, Monteleoni 1996) and planning (NEMO, Riccobene 2001; see Halzen 2001 for a recent review).

In this paper we consider a class of identified Galactic microquasars with either persistent jets or documented outbursts. For each source we provide, for illustrative purposes, our model prediction for the neutrino flux that should have been emitted during particular events, using radio data available in the literature. Although the temporal behaviour of many of these sources may be unpredictable, we demonstrate that some of the sources could have been detected by a neutrino telescope with effective area larger than  $\text{km}^2$  (in some cases even  $0.1 \text{ km}^2$ ) had such a detector been in operation during the time of the recorded events and, therefore, propose that they should be potential targets for the planned neutrino telescopes. In addition we consider a list of XRBs thus far unresolved at radio wavelengths, that are believed to be microquasar candidates. In §2 we briefly discuss the neutrino production mechanism in microquasars. In §3 we use observational data available for each source to estimate the jet parameters, and then use these parameters to derive the expected neutrino flux. The number of neutrino induced muon events in  $\text{km}^2$ -scale neutrino telescopes is derived in §4. The implications of our results are briefly discussed in §5.

## 2. Internal shock model for microquasars

In order to introduce the parameters relevant for the present analysis, we give in this section a brief outline of the model proposed by Levinson & Waxman (2001) for production of neutrinos in microquasars. The model assumes that on sufficiently small scale ( $\leq 10^{11}$  cm), inhomogeneities in the jet cause internal shocks which can accelerate protons and electrons to a power law distribution. The maximum proton energy is determined by equating the acceleration time, estimated as the Larmor radius divided by  $c$ , to the smallest of the dynamical time and the loss time due to photomeson interactions. For typical jet parameters, this energy is roughly  $10^{16}$  eV in the jet frame. Protons can interact both with the external X-ray photons emitted by the accretion disc and with the synchrotron photons produced inside the jet by the accelerated electrons, leading to pion production and consequently to neutrino emission. In order for photomeson production to take place, the comoving proton

energy must exceed the threshold energy for  $\Delta$ -resonance,  $\approx 10^{14}$  eV for interaction with the external photons and  $\approx 10^{13}$  eV for interaction with synchrotron photons.

Charged pions produced in photo-meson interactions decay to produce neutrinos,  $\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$ . In a single collision, a pion is created with an average energy which is  $\approx 20\%$  of the proton energy. This energy is roughly evenly distributed between the final  $\pi^+$  decay products, yielding a  $\nu$  energy which is  $\approx 5\%$  of the proton energy. The fraction of proton energy converted into pions,  $f_\pi$ , depends on the jet Lorentz factor,  $\Gamma$ , and on the kinetic luminosity of the jet,  $L_{jet}$ . Levinson & Waxman (2001) find that for protons of energy  $\epsilon_p = \epsilon_{p,peak} \approx 10^{13}$  eV, interacting with the peak of the synchrotron photon spectrum, the fraction of energy converted to pions is approximately given by

$$f_{\pi,peak} \simeq \min \left[ 1, 0.1\eta_{e,-1}^{1/2}\Gamma^{-2}\phi_{0.2}^{-1}L_{j38}^{1/2} \right], \quad (1)$$

where  $L_j = 10^{38}L_{j38}$  erg s $^{-1}$  and  $\phi = 0.2\phi_{0.2}$  are the jet kinetic power and opening angle, and  $\eta_e = 0.1\eta_{e,-1}$  is the fraction of jet energy converted to relativistic electrons (and hence to radiation).  $f_\pi$  increases with proton energy;  $f_\pi \propto \epsilon_p^{1/2}$  beyond the peak. However, using the analysis of Levinson & Waxman, we find that the maximum proton energy for which the decay time of the  $\pi^+$  produced in the photo-meson interaction is shorter than its synchrotron energy loss time, is  $\approx 10\epsilon_{p,peak}$ . Since we are interested only in production of pions that decay to produce neutrinos, and since the neutrino signal is dominated by neutrinos in the energy range of 1 to 100 TeV, we use in what follows the value given in Eq. (1) as the characteristic value of  $f_\pi$  for protons in the energy range relevant for production of neutrinos that contribute to the observed signal.

The expected fluence (energy per unit area) of  $\gtrsim 1$  TeV muon neutrinos at Earth from a jet ejection event is (Levinson & Waxman 2001)

$$F_{\nu_\mu} \simeq \frac{1}{2}\eta_p f_\pi \Gamma^{-1} \delta^3 \frac{E_{jet}/8}{4\pi D^2}, \quad (2)$$

where  $\delta = [\Gamma(1 - \beta \cos \theta)]^{-1}$  is the Doppler factor of the jet ( $\theta$  is the angle between the jet axis and our line of sight),  $\eta_p \sim 0.1$  the fraction of  $L_{jet}$  carried by accelerated protons, and  $D$  is the source distance.  $E_{jet}$  is the total energy carried by the jet during the event duration (jet life time). The corresponding neutrino flux is

$$f_{\nu_\mu} \simeq \frac{1}{2}\eta_p f_\pi \delta^4 \frac{L_{jet}/8}{4\pi D^2}. \quad (3)$$

### 3. Jet parameters and neutrino fluxes

As explained in the introduction the term microquasar refers to XRBs that reveal relativistic jets resolved in the radio band. In events that have been monitored with sufficiently good resolution, it is often possible to obtain a rough estimate of the characteristic source parameters, in particular the bulk speed of the jet, the angle between the jet axis and the sight line, and the size of the emitting blob. Several other X-ray binaries, such as Cygnus X-1, have been observed as point-like radio sources (Fender & Kuulkers 2001). The spectrum emitted by those sources and the high degree of polarization sometimes measured is consistent with synchrotron emission by nonthermal electrons. Moreover, their temporal behaviour appears to be similar to that seen in the resolved microquasars and, therefore, it is tempting to conjecture that they belong to the microquasar class. Since the putative jets are unresolved in these objects, we use a different method to estimate the kinetic power of their jets. In what follows, we consider separately the resolved and unresolved sources.

#### 3.1. Resolved microquasars

In order to determine the neutrino flux from equation (3), we use for each observed microquasar values of  $\Gamma$ ,  $\delta$  and  $D$  quoted in literature.  $L_{jet}$  is estimated in the following way: for a flux density  $S_\nu \propto \nu^{-1/2}$  of the source, implying an electron energy distribution  $dn_e/d\epsilon_e \propto \epsilon_e^{-2}$ , the minimum energy carried by electrons and magnetic field is obtained for a magnetic field [e.g. (Levinson & Blandford 1996)]:

$$B_* = 3.6 \left[ \ln(\gamma_{\max}/\gamma_{\min}) \frac{T_{B6}}{l_{15}} \right]^{2/7} \frac{\nu_9^{5/7}}{\delta} \text{ mG}, \quad (4)$$

where  $\nu = \nu_9 \cdot 10^9$  Hz,  $l = l_{15} \cdot 10^{15}$  cm is the size of the emission region,  $\gamma_{\max}$  and  $\gamma_{\min}$  are the maximum and minimum electron random Lorentz factors as measured in the jet frame, and  $T_B = 10^6 T_{B6}$  K is the brightness temperature:  $T_B \equiv c^2 S_\nu / 2\pi (l/D)^2 \nu^2$ . The minimum jet luminosity carried by electrons and magnetic field is  $L_{jet,eB} \geq (7/3)\pi l^2 c \Gamma^2 (B_*^2/8\pi)$ . Denoting by  $\eta_e$  the fraction of jet kinetic energy converted to internal energy of electrons and magnetic field, we finally obtain

$$L_{jet} \geq \frac{7}{24} c \frac{(\Gamma l B_*)^2}{\eta_e}. \quad (5)$$

For the numerical estimates that follow we conservatively assume  $\gamma_{\max}/\gamma_{\min} = 100$ .

As an example, consider the March 1994 event observed in GRS 1915+105. This source is at a distance of  $\sim 12.5$  kpc from Earth. On March 24<sup>th</sup> 1994 the flux, measured with the VLA at a wavelength of 3.5 cm, was 655 mJy. Even though the source was not resolved at the

time, the inferred size of the blob was  $60 \times 20$  mas (Mirabel & Rodríguez 1994). Assuming a spherical blob the corresponding blob radius is  $l_{15} \sim 2$ . The estimated speed of the ejecta is  $\beta \sim 0.92$  at an angle to the line of sight of  $\theta \sim 70^\circ$ . Using Eqs. (5), (4) we obtain  $T_B \sim 4 \cdot 10^7$  K,  $B_* \sim 110$  mG and  $L_{jet} \sim 2.5 \cdot 10^{40} \eta_{e,-1}^{-1}$  erg/sec. Here,  $\eta_e = 0.1 \eta_{e,-1}$ .

A similar analysis was carried out for the other sources. In Table 1 we report our estimates of brightness temperature, equipartition magnetic field and jet power for the list of known microquasars, resolved in the radio band. In the same table we also report the values of parameters required for our calculations. The two values of the periodic source LS I +61°303 (P~26.5 days) refer respectively to bursting and quiescent states observed by Massi et al. (2001). The parameters for V4641 Sgr are uncertain. The distance to this source has been estimated by Orosz et al. (2001) to lie in the range between 7.4 and 12.5 kpc, based on their estimate of the parameters of the companion star. This is in contrast to a distance of  $\sim 0.5$  kpc that seems to be favored by Hjellming et al. (2000). The former implies a jet with Lorentz factor atypically high ( $\Gamma \sim 22$ ), directed along our line of sight and, consequently, a much higher neutrino flux. In tables 1 and 2 we list the parameters and neutrino fluxes obtained for both these distance estimates.

The steady source SS433 ( $D = 3$  kpc,  $\beta \sim 0.3$  and  $\theta \sim 79^\circ$ ) is not present in Table 1. In order to estimate the kinetic luminosity of the jet for this source our simplified model cannot be applied. The source is surrounded by the diffuse nebula W50, maybe a supernova remnant. Several authors pointed out that the kinetic energy output of the SS433 jets can influence the radio emission of W50; moreover SS433 is the only microquasar which shows a strong  $H_\alpha$ -line emission from the jets (Begelman 1980; Davidson & McCray 1980; Kirshner & Chevalier 1980). In our estimate we assume the conservative value of  $L_{jet} \sim 10^{39}$  erg/sec suggested by Margon (1984).

In Table 2 we report the neutrino flux for the listed microquasars, calculated using equation 3 and considering the different values of  $f_\pi$  given by Eq. (1).

### 3.2. Unresolved microquasars

For the sources whose jet has not been resolved, we cannot deduce the value of  $L_{jet}$  from Eq.(5), since  $\Gamma$ ,  $\delta$  and the size of the jet are not known. We follow instead a different line of argument. We define the jet synchrotron luminosity as

$$L_{syn} = 4\pi D^2 \frac{1}{1 - \alpha_R} S_{\nu_{high}} \nu_{high}, \quad (6)$$

where  $\alpha_R$  is the spectral index,  $\nu_{high}$  the highest observed frequency of synchrotron emission, and  $S_{\nu_{high}}$  the flux density at this frequency. We assume, as in the previous section, that a fraction  $\eta_e \sim 0.1$  of the jet kinetic energy is converted to relativistic electrons and magnetic field. The radio spectral index is typically  $\alpha_R \simeq 0.5$ , implying that the electrons do not cool fast on scales that are resolved by the VLA, and hence lose only a small fraction of their energy to synchrotron emission. In fact, assuming that the emission at  $\nu_{high}$  originates from the same radius as the radio emission, then for the typical parameters inferred for the resolved MQs, that is, B on the order of tens of mG and a corresponding synchrotron frequency of about 10 GHz, electrons radiating at  $\nu_{high} \sim 10^{15}$  Hz can not lose more than  $\eta_r \sim 0.1$  of their energy. It could well be however that the optical emission is produced at much smaller radii, in which case  $\eta_r$  may be of order unity. Given the above, we estimate the jet luminosity as

$$L_{jet} = \eta_e^{-1} \eta_r^{-1} L_{syn}, \quad (7)$$

and the neutrino flux at Earth as

$$f_{\nu_\mu} = \frac{1}{2} f_\pi \eta_p \frac{L_{jet}/8}{4\pi D^2} = \frac{1}{16(1 - \alpha_R)} \frac{\eta_p}{\eta_e} f_\pi \eta_r^{-1} S_{\nu_{high}} \nu_{high}. \quad (8)$$

We have neglected in eqs. (6–8) corrections due to relativistic expansion of the jets. However, since these corrections are the same for both the synchrotron and neutrino emission, the estimate of neutrino flux in eqs. (8) is independent of such corrections. In Table 3 we quote, for the sample of unresolved microquasar candidates, the values of  $\nu_{high}$  and  $S_{\nu_{high}}$ , the distance of the source and our estimates of  $L_{jet}$  and  $f_{\nu_\mu}$ , calculated from Eq. (7) and Eq.(8).

#### 4. Muon events expected in a km<sup>2</sup>-scale detector

The detection of TeV neutrino fluxes from microquasars could be the first achievable goal for proposed underwater(ice) neutrino telescopes. In this section we calculate the rate of neutrino-induced muon events expected in a detector with an effective area of 1km<sup>2</sup>. We also calculate the number of atmospheric neutrino induced muon events expected in such a detector in order to estimate the signal to noise ratio. Since the signal is expected to be dominated by neutrinos of energy  $E_\nu \geq 1$  TeV, for which the detection probability is  $P_{\nu_\mu} \sim 1.3 \cdot 10^{-6} E_{\nu, TeV}$  (Gaisser *et al.* 1995), we estimate the rate of neutrino-induced muon events as (Levinson & Waxman 2001):

$$\dot{N}_\mu \simeq 0.2 \eta_{p,-1} f_\pi \delta^4 D_{22}^{-2} L_{jet,38} A_{\text{km}^2} \text{ day}^{-1} \quad (9)$$

where  $A_{\text{km}^2}$  is the effective detector area in km<sup>2</sup> units. The total number of muon events in the detector is obtained by multiplying the muon rate given by Eq. (9) by the duration,

$\Delta t$ , of the observed burst. In Table 4 we report the number of events expected in a detector with  $A_{eff} = 1 \text{ km}^2$ , during the bursts considered in section 3. In the case of persistent sources, the number of neutrino induced muon events, reported in Table 4, is calculated for a 1 year period. In the same table, we also report the number of atmospheric neutrino events collected in such a detector during the time  $\Delta t$ . For the background calculation, we assume a neutrino spectrum  $\phi_{\nu, bkg} \sim 10^{-7} E_{\nu, \text{TeV}}^{-2.5} / \text{cm}^2 \text{ sec sr}$  for  $E_{\nu} > 1 \text{ TeV}$ ,  $A_{\text{km}^2} = 1$  and a detector angular resolution of  $0.3^\circ$ . Our calculations suggest that microquasar signals may be identified well above the atmospheric neutrino background by the next generations of underwater(ice) neutrino telescopes.

In order to estimate the event rates for non-persistent sources it is crucial to know their duty cycle. Some of these sources show a periodic bursting activity: Circinus X-1 has a period of 16.59 days (Preston *et al.* 1983), LS I +61 °303 exhibits a 26.5 day periodic non thermal outburst (Massi *et al.* 2001) and in the tables we give the results for both the quiescent and the bursting phase. Other transient sources show a stochastic bursting activity. For such cases it is difficult to give an estimate of the expected event rate. For example, in the campaign of August-December 1994 the lightcurves of GRO J1655-40 were dominated by three radio flares, each lasting for 6 days (Hjellming & Rupen 1995); In the campaign of February-April 1994 GRS 1915+105 has exhibited 4 bursts (Rodríguez & Mirabel 1999).

## 5. Discussion

There are large uncertainties involved in the derivation of the jet parameters for most of the sources listed in table 4. The best studied cases are perhaps GRS 1915+105, GRO J1655-40, and SS433. Nonetheless, we have demonstrated that if the jets in microquasars are protonic, and if a fraction of a few percent of the jet energy is dissipated on sufficiently small scales, then emission of TeV neutrinos with fluxes in excess of detection limit of the forthcoming,  $\text{km}^2$  scale, neutrino telescopes is anticipated. Table 5 shows the fraction of the time during which each of the sources analyzed in this paper can be observed, i.e. the number of hours per day during which the source is under the horizon and may therefore produce upward moving muons, in a northern hemisphere and a southern hemisphere detector. The present identification of microquasars, and the inferred distribution of their jet Lorentz factors, may be strongly influenced by selection effects. It is quite likely that the class of Galactic microquasars contains also sources with larger bulk Lorentz factors and smaller viewing angles, which should emit neutrinos with fluxes considerably larger than the extended microquasars discussed in this paper. Such sources may be identified via their gamma-ray emission with, e.g. AGILE and GLAST, or by their neutrino emission. The gamma-rays should originate



from larger scales where the pair production opacity is sufficiently reduced. Predictions for AGILE and GLAST will be discussed in a forthcoming paper (Guetta *et al.* 2002). There are currently about 280 known XRBs (Liu *et al.* 2000; Liu *et al.* 2001), of which  $\sim 50$  are radio loud. These may also be potential targets for the planned neutrino detectors. Our results quoted in Tables 2 and 3 are consistent with experimental upper limits on neutrino fluxes from point sources set by MACRO (Ambrosio 2001), AMANDA (Biron 2002) and SuperKamiokande (Okada 2000). The MACRO upper limits (Ambrosio 2001) for microquasar fluxes are shown in table 6. For the brightest sources in our table, SS433 and GX 339-4, the MACRO bounds are approximately an order of magnitude larger than our predicted fluxes.

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Table 1. Brightness temperature, magnetic field and jet kinetic luminosity of identified Galactic microquasars, and the parameters (inferred from observations) on which they are based (see text).

Source name	D (kpc)	$\theta$ (deg)	$\beta$	$\Gamma$	$\delta$	$l_{15}$	$\nu$ (GHz)	$S_\nu$ (mJy)	$T_B$ (K)	$B_*$ (mG)	$\eta_{e,-1} L_{jet}$ (erg/sec)	Ref.
CI Cam	1	83	0.15	1.01	1.01	0.8	22.5	450	$1.57 \cdot 10^5$	33.5	$5.66 \cdot 10^{37}$	1,2
XTE J1748-288	8	64	0.73	1.46	1.01	15.0	4.9	410	$4.90 \cdot 10^5$	6.6	$1.84 \cdot 10^{39}$	3,4,5
Cygnus X-3	10	14	0.81	1.70	2.74	0.23	15	10500	$8.47 \cdot 10^9$	288.7	$1.17 \cdot 10^{39}$	6
LS 5039	3	68	0.4	1.09	1.08	0.04	5.0	16	$2.83 \cdot 10^8$	203	$8.73 \cdot 10^{36}$	7
GRO J1655-40	3.1	81	0.92	2.55	0.46	4.7	1.6	3400	$5.86 \cdot 10^7$	35.9	$1.60 \cdot 10^{40}$	8
GRS 1915+105	12.5	70	0.92	2.55	0.57	1.9	8.6	655	$3.94 \cdot 10^7$	110	$2.45 \cdot 10^{40}$	9
Circinus X-1	10	70	0.1	1.01	1.03	1.1	2.3	1200	$1.78 \cdot 10^9$	82.3	$7.61 \cdot 10^{38}$	4,10
LS I 61°303	2	0.2	0.43	1.11	1.58	0.2	5.0	220	$1.55 \cdot 10^8$	82.6	$1.65 \cdot 10^{37}$	11
LS I 61°303	2	0.2	0.43	1.11	1.58	0.2	5.0	34	$2.40 \cdot 10^7$	48.4	$5.69 \cdot 10^{36}$	11
XTE J1550-564	2.5	74	0.83	1.79	0.72	1.1	2.3	71	$6.64 \cdot 10^6$	23.7	$2.01 \cdot 10^{38}$	12,13
V4641 Sgr	0.5	63	0.85	1.90	0.86	0.9	4.9	400	$4.71 \cdot 10^5$	17.0	$8.02 \cdot 10^{37}$	14
V4641 Sgr	9.6	6	0.999	22.37	6.91	18.0	4.9	400	$4.71 \cdot 10^5$	0.91	$1.17 \cdot 10^{40}$	14,15
Scorpius X-1	2.8	44	0.95	3.20	0.99	0.06	5	20	$1.57 \cdot 10^8$	170.4	$1.04 \cdot 10^{38}$	16,17

References. — (1) Hjellming & Mioduszewski 1998, (2) Harmon & Fishman 1998, (3) Rupen & Hjellming 1998, (4) Mirabel & Rodríguez 1999, (5) Kotani *et al.* 2000, (6) Mioduszewski *et al.* 2001, (7) Paredes *et al.* 2000, (8) Hjellming & Rupen 1995, (9) Mirabel & Rodríguez 1994, (10) Preston *et al.* 1983, (11) Massi *et al.* 2001, (12) Hannikainen *et al.* 2001, (13) Sanches-Fernandez 1999, (14) Hjellming *et al.* 2000, (15) Orosz *et al.* 2001, (16) Fomalont *et al.* 2001a, (17) Fomalont *et al.* 2001b.

Table 2:  $> 1$  TeV neutrino flux at Earth from identified Galactic microquasars, estimated using Eq. (3).

Source name	$f_{\pi,peak}$	$\eta_{p,-1}^{-1}\eta_{e,-1}^{1/2}f_{\nu}$ (erg/ cm <sup>2</sup> sec)
CI Cam	0.07	$2.23 \cdot 10^{-10}$
XTE J1748-288	0.20	$3.07 \cdot 10^{-10}$
Cygnus X-3	0.12	$4.02 \cdot 10^{-9}$
LS 5039	0.02	$1.69 \cdot 10^{-12}$
GRO J1655-40	0.19	$7.37 \cdot 10^{-10}$
GRS 1915+105	0.24	$2.10 \cdot 10^{-10}$
Circinus X-1	0.27	$1.22 \cdot 10^{-10}$
LS I 61°303	0.03	$4.49 \cdot 10^{-11}$
LS I 61°303	0.02	$9.06 \cdot 10^{-12}$
XTE J1550-564	0.04	$2.00 \cdot 10^{-11}$
V4641 Sgr	0.02	$2.25 \cdot 10^{-10}$
V4641 Sgr	0.002	$3.25 \cdot 10^{-8}$
Scorpius X-1	0.01	$6.48 \cdot 10^{-12}$
SS433	0.29	$1.72 \cdot 10^{-9}$

Table 3: Kinetic jet luminosity,  $L_{jet}$ , and  $> 1$  TeV neutrino flux at Earth,  $f_{\nu_\mu}$ , for unresolved microquasars, estimated using Eqs. (7) and (8). D is the source-observer distance,  $\nu_{high}$  is the highest frequency at which synchrotron emission is observed,  $S_\nu$  is the flux density measured at  $\nu = \nu_{high}$ .

Source name	D (kpc)	$\nu_{high}$ ( $10^{14}$ Hz)	$S_\nu$ (mJy)	$L_{jet}$ (erg/sec)	$(\eta_e/\eta_p)(\eta_{r,-1}/f_\pi)f_{\nu_\mu}$ (erg/cm <sup>2</sup> sec)	Ref.
GS 1354-64	10	3	5	$3.62 \cdot 10^{37}$	$1.88 \cdot 10^{-11}$	1,2
GX 339-4	4	10	100	$3.86 \cdot 10^{38}$	$1.26 \cdot 10^{-9}$	1,3,4
Cygnus X-1	2	1	15	$1.45 \cdot 10^{36}$	$1.88 \cdot 10^{-11}$	3,5
GRO J0422+32	3	4	50	$4.35 \cdot 10^{37}$	$2.51 \cdot 10^{-10}$	1,6
XTE J1118+480	1.9	20	20	$3.49 \cdot 10^{37}$	$5.02 \cdot 10^{-10}$	1,7

References. — (1) Fender 2000, (2) Brocksopp 2001, (3) Fender 2001b, (4) Corbel *et al.* 2000, (5) Pooley *et al.* 1999, (6) Shrader 1994, (7) Frontiera 2001.

Table 4: Predicted number of muon events,  $N_\mu$ , in a  $1\text{km}^2$  detector, based on the neutrino fluxes given in tables 2 and 3. For bursting sources, the number of events expected in a burst of duration  $\Delta t$  is quoted. For persistent sources, 1 year integration time is assumed. The two values quoted for the periodic source LS I +61°303 refer to a bursting state of duration 7 days and to a quiescent state of duration  $\sim 20$  days.  $N_{\mu,bkg}$  is the expected number of background atmospheric neutrino events, assuming angular resolution of  $0.3^\circ$ .

Source name	$\Delta t$ (days)	$N_\mu$	$N_{\mu,bkg}(deg/0.3^\circ)^2$
CI Cam	0.6	0.05	0.002
XTE J1748-288	20	2.5	0.054
Cygnus X-3	3	4.8	0.008
LS 5039	persistent	0.2	0.986
GRO J1655-40	6	1.8	0.016
GRS 1915+105	6	0.5	0.016
Circinus X-1	4	0.2	0.011
LS I 61°303	7	0.1	0.019
LS I 61°303	20	0.1	0.054
XTE J1550-564	5	0.04	0.014
V4641 Sgr	0.3	0.03	0.001
V4641 Sgr	0.3	3.9	0.001
Scorpius X-1	persistent	0.9	0.986
SS433	persistent	252	0.986
GS 1354-64	2.8	0.02	0.008
GX 339-4	persistent	183.4	0.986
Cygnus X-1	persistent	2.8	0.986
GRO J0422+32	$1 \div 20$	$0.1 \div 2$	$0.003 \div 0.1$
XTE J1118+480	$30 \div 150$	$6 \div 30$	$0.081 \div 0.405$

Table 5: Microquasar equatorial coordinates and the fraction of time (hours per day) during which the source is below the horizon, and can hence be observed by a neutrino telescope, for a telescope located at Lat.  $36^\circ 23' 51''$  N (NEMO, Mediterranean sea),  $T_N$ , and for a neutrino telescope located at the South Pole (Amanda-IceCube),  $T_I$ .

Source name	Right Ascension	Declination		$T_N$ (hours)	$T_I$ (hours)
CI Cam	$4^h 19^m 42^s.2$	$+55^\circ 59' 58''.0$	(2000)	0	24
XTE J1748-288	$17^h 48^m 05^s.1$	$-28^\circ 28' 25''.8$	(2000)	15.1	0
Cygnus X-3	$20^h 32^m 26^s.6$	$+40^\circ 57' 09''.0$	(2000)	6.7	24
LS 5039	$18^h 26^m 14^s.9$	$-14^\circ 50' 51''.0$	(2000)	13.5	0
GRO J1655-40	$16^h 54^m 0^s.2$	$-39^\circ 50' 44''.7$	(2000)	17.0	0
GRS 1915+105	$19^h 12^m 50^s.0$	$+10^\circ 51' 27''.0$	(1950)	10.9	24
SS433	$19^h 11^m 49^s.6$	$+04^\circ 58' 58''.0$	(2000)	11.5	24
Circinus X-1	$15^h 16^m 48^s.3$	$-56^\circ 59' 14''.0$	(1950)	24	0
LS I $+61^\circ 303$	$2^h 40^m 31^s.7$	$+61^\circ 13' 45''.6$	(2000)	0	24
XTE J1550-564	$15^h 50^m 58^s.7$	$-56^\circ 28' 35''.3$	(2000)	24	0
V4641 Sgr	$18^h 19^m 21^s.5$	$-25^\circ 25' 36''.0$	(2000)	14.7	0
Scorpius X-1	$16^h 19^m 55^s.1$	$-15^\circ 38' 24''.9$	(2000)	13.6	0
GS 1354-64	$13^h 58^m 09^s.7$	$-64^\circ 44' 05''.0$	(2000)	24	0
GX 339-4	$17^h 02^m 49^s.5$	$-48^\circ 47' 23''.0$	(2000)	19.6	0
Cygnus X-1	$19^h 58^m 21^s.7$	$+35^\circ 12' 05''.8$	(2000)	7.8	24
GRO J0422+32	$4^h 21^m 42^s.7$	$+32^\circ 54' 27''.0$	(2000)	8.2	24
XTE J1118+480	$11^h 18^m 17^s.0$	$+48^\circ 3' 0''.0$	(2000)	4.7	24



Table 6: Upper limit (90% c.l.) on  $> 1$  TeV neutrino fluxes from individual microquasars, inferred from the MACRO upper limit on the number flux of  $> 1$  GeV neutrinos,  $f_{\#}(> 1\text{GeV})$ , from these sources ((Ambrosio 2001)). Since the MACRO limit is derived assuming a neutrino spectrum  $dn_{\nu}/d\epsilon_{\nu} \propto \epsilon^{-2}$ , the inferred limit on 1 TeV to 100 TeV neutrino energy flux is  $\approx \ln(100)f_{\#}(> 1\text{GeV}) \times 1 \text{ GeV}$ .

Source name	MACRO upper limits ( $\text{erg cm}^{-2} \text{ s}^{-1}$ )
Circinus X-1	$1.77 \times 10^{-8}$
GX 339-4	$2.40 \times 10^{-8}$
SS433	$1.02 \times 10^{-8}$
Cygnus X-1	$4.99 \times 10^{-8}$
Cygnus X-3	$9.99 \times 10^{-8}$
Scorpius X-1	$1.27 \times 10^{-8}$